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Local Universe Science with the E-ELT

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Abstract. This paper briefly reviews some of the exciting studies of the local Universe that will be enabled with the European Extremely Large Telescope (E-ELT). As illustrative examples, it summarizes a few of the scientific goals that have been set for this instrument for studies of young starburst clusters, evolved stars, the Galactic centre, Galactic structure, nucleo-chronometry, the interpretation of the “Spite Plateau,” and the properties of resolved stellar populations in external galaxies. It finishes on a note of warning that we really need to be even more innovative and adventurous if we are to justify the cost of the E-ELT.

1. Introduction

There is not a great deal of point in trying to reproduce the full local Universe science case for the European Extremely Large Telescope (E-ELT) within these few pages for two reasons. First, there already exist far more comprehensive documents that seek to describe the science that this amazing telescope will enable (Hook 2005), not to mention the mass of science ideas that have been put together by various instrument teams in developing Phase A studies and related documents (from which I borrow quite extensively in this article). There are also the documents that describe the science to be undertaken with other future large telescopes (e.g. Silva et al. 2007), as well as the cases that were developed for projects that have now been dropped or merged with the current programme (e.g. Andersen et al. 2003), all of which overlap significantly with the E-ELT case. Second, even the most optimistic timetable places first light for E-ELT eight years off. One thing that we learned from the Hubble Space Telescope (HST) was that the detailed science cases for such long timescale projects are frequently overtaken by developments in the field long before they are completed. This is not to say that such science cases are not important, as they demonstrate the kind of science that a telescope can do, nor that there will be nothing left to do once the telescope is completed – as we have seen with HST, it is in the nature of telescopes that they are remarkably flexible tools that can be turned to a fascinating variety of tasks that were not envisaged when they were designed. Nonetheless, it does indicate that it is not worth trying to be too definitive in a short review like this, so I will instead concentrate on broader themes and examples that illustrate the range of science that we will be able to undertake.

I also need to define a little more clearly what is meant by the “local Universe,” since this term clearly refers to

different scales if one is studying solar physics or galaxy morphology. Perhaps the most useful definition is that this phrase describes a large enough volume of the Universe to contain a representative sample of the object under study, but not so large that the finite speed of light means that we start seeing cosmic evolution in the population. Note that there is no guarantee that such a range of distances exists: for example, bright quasars are so rare that any decent-sized sample will span a range of redshifts that starts to probe the cosmic evolution of the quasar population. Nonetheless, it makes a reasonable working definition for the purposes of this review. Indeed, it was this definition that provided one of the principal science drivers for a telescope as large as the E-ELT: if we are to use this instrument to study the detailed properties of galaxies, we need to sample a region that contains all the environments in which these objects typically reside, including clusters. The closest such reasonably-rich systems are the Virgo Cluster and the Fornax Cluster, which motivated the requirement for a telescope that can study resolved stellar populations at distance of ~ 20 Mpc.

In the remainder of this paper, a number of examples of this kind of local Universe science that will be enabled with the E-ELT are briefly outlined, while Section 9 concludes with a cautionary note about the risks of over-reliance on such cases.

2. Young Starburst Clusters

An excellent example of the ability of the E-ELT to allow us to study a more representative sample of the Universe is provided by young starburst clusters. At present, the only two such clusters that can be studied in any detail are Westerlund 1 and 2. Even these relatively nearby examples, at distances of only a few kiloparsecs, are difficult to study, lying in the Galactic plane and hence being obscured by visual extinctions of $A_V \sim 13$ and 5 respec-

tively (Piatti, Bica & Claria 1998). With the E-ELT, we will win over current technology in several ways. First, the large collecting area provides an effective mechanism for penetrating extinction and seeing more distant clusters. Second, the availability of mid-infrared instrumentation will allow us to explore the properties of these systems at wavelengths that are much less affected by such extinction. Third, the unprecedented spatial resolution will allow us to resolve individual stars, even in much more distant clusters, allowing us to study their individual properties. In this way, we will also be able to study starburst clusters in other parts of spiral arms, such as NGC 3603 further out along the Sagittarius Arm, and RSGC 1 much further in along the Scutum-Crux Arm (Davies et al. 2007). Similar attention can also be focused on the two starburst systems near the Galactic Centre, the Arches Cluster and the Quintuplet Cluster.

Particular observations that could be made to study these systems include measuring individual stellar proper motions to identify cluster members unequivocally, resolving their stellar luminosity functions all the way down to sub-stellar masses, and studying the properties of the individual stars, such as searching for the signatures of planetary disks from their mid-infrared spectra. By exploring examples all along the arms of a typical spiral galaxy like the Milky Way as well as those forming near the centre of the Galaxy, we will be able to search for any variations with environment, some of which would have far-reaching consequences. For example, if for some reason planetary systems were only found to start to form in clusters over a limited range of environments, that would have major implications for the study and understanding of exo-planets.

3. Evolved Stars

At the other end of stellar evolution from the young starburst clusters, the E-ELT will also shed new light on stars as they near the ends of their lives. Here, the issue is that this phase of stellar evolution is short, so these objects are rare and the number accessible to study with 8-metre telescopes is very limited. Even with the few nearby examples, the subtlety of the spatial structure in dust emission as these objects lose their outer envelopes means that very high resolution mid-infrared data are required to understand their properties (e.g. Weigelt et al 1998). With the reach of the E-ELT, we will finally be in a position to study a representative sample of these objects, quantify the range of morphologies that they display as they shed their outer envelopes, explore the spatially-resolved emission from a range of molecules, and investigate how these properties vary with environment. In other words, for the first time we will be able to study them properly in the context of the local Universe.

4. The Galactic Centre

Another new vista opened up by the E-ELT will be that of the Galactic Centre. Although we have been studying

the properties and motions of stars in this region for quite some time (Ghez et al. 2000; Genzel et al. 2000), we are really only exploring the tip of the iceberg. For example, there is some evidence that the Galactic Centre region is not conducive to the formation of lower-mass stars (Nayakshin & Sunyaev 2005), but it will only be with the E-ELT that we will be able to explore the luminosity function at very small radii in the Galaxy all the way down to sub-stellar masses, to see quite how important this effect really is.

The dynamics of these stars also offer an unprecedented probe of a galactic nucleus: Weinberg, Milosavljevic & Ghez (2005) showed that a telescope like the E-ELT will be able to determine the distribution of mass in any central dark matter cusp from its effect on the orbits of stars, as well as measuring the mass of the central black hole with high precision. By comparing the proper motions of stars near the Galactic Centre to their line-of-sight velocities inferred from spectra, Weinberg et al. also showed that one will be able to determine the distance to the Galactic Centre to a fraction of a percent. They argue that such a measurement could be used to remove the major uncertainty from current measurements of the shape of the Galactic halo, which is a useful diagnostic of the nature of dark matter (Olling & Merrifield 2000).

Here we have to be a little careful, however, as while the Milky Way may be a typical system, there is likely to be significant variance from galaxy to galaxy in quantities such as central black hole mass and halo flattening. Thus, while such measurements may be of interest, we are not really meeting the requirement on “local Universe” science that we are exploring a representative sample of objects, so ever more precise measurements may not translate into ever more accurate scientific conclusions.

5. The Fingerprints of Galactic Structure

Simulations have shown that the stellar halo of a galaxy like the Milky Way is likely to be a messy tangle of stellar streams from destroyed merging satellites (Bullock & Johnston 2005). Indeed, the brightest and youngest such streams are now readily accessible to observation (Belokurov et al. 2006). As time passes, these streams become wrapped and tangled to a point where they are no longer detectable as photometric enhancements, so we cannot dig far back into the formation of the Milky Way halo from such data. However, in the phase space of positions and velocities, their coherent structure remains apparent for much longer, particularly if there is some way to tag stars as likely having a common origin. Similarly, within the disk of the Milky Way one might hope to determine which stars originated in the same stellar nurseries long after they have spread out around the Galaxy. In this regard, it is potentially invaluable that stars originating in the same stellar cluster seem to have identical detailed chemical abundances, but that those abundances vary significantly from cluster to cluster (de Silva et al.

2007). Thus by obtaining high-resolution spectra of Milky Way stars, one not only measures the line-of-sight velocity component of the phase space coordinates, and spectral indices that may provide an indication of properties such as the star's age and metallicity, but one also obtains a "fingerprint" of the star that will uniquely tie it to its siblings. Ryde (2010) has demonstrated that appropriate diagnostic lines exist in the near infrared for the E-ELT to exploit in exactly this exercise.

Most of the existing data at reasonably large distances (such as the Galactic bulge) has been obtained from red giant stars, in which convective mixing of processed material will have erased at least some of these identifying chemical tags. It has therefore not proved possible to use such data to obtain unequivocal properties of these stars and their origins, and one would really want to obtain spectra of main-sequence stars where the chemical signals are much clearer. The collecting area of E-ELT will enable us to obtain the necessary high-resolution spectra of main-sequence stars all across the Galaxy to perform such studies. However, we can already obtain a taste of what is to come by using what might be called the " μ -ELT," the microlensing extremely large telescope. Bensby et al. (2010) have been exploiting the microlensing of bulge stars by foreground objects, which amplifies their brightness to a point where high-resolution spectra of even intrinsically-faint main sequence stars can be obtained using 8-metre telescopes. This analysis has shown that bulge main-sequence stars have tightly correlated properties in their chemical abundances, similar to those seen in thick-disk stars, which offers an important new clue to their origins. These data also show that such spectra can provide reliable age diagnostics for stars near the main-sequence turn-off. However, at present the data are limited by the rate at which such rare microlensing events occur; with E-ELT, we will be able to make such measurements for many times the sample of 15 stars for which Bensby et al. (2010) have been able to obtain observations.

6. Nucleo-Chronometry

With the kind of very high-resolution, very high signal-to-noise ratio spectroscopy that is only possible with the light collecting power of the E-ELT, one can attempt to make novel measurements that are almost impossible at the moment. For example, determination of the abundances of heavy elements like uranium have only been made for a tiny number of stars, and even in those cases the systematic uncertainties in the measurements are quite large (Frebel et al. 2007). The motivation to make such measurements is that these heavy elements are frequently radioactive, so their abundances decrease with time. By measuring those abundances relative to a non-decaying similar element, one obtains a completely different innovative measure of stellar age. This "clock," unlike more conventional measures like the main-sequence turn-off, depends only on the basic physics of radioactive decay, so is a very robust measurement. Further, it is sufficiently slow

running that it can be applied reliably to very old stars, giving a strong and independent lower bound on the age of the Universe (Frebel et al. 2007). Such observations with the E-ELT at very high resolution will reduce the systematic errors on these subtle measurements, while observing much larger samples than are currently accessible will increase the age of the oldest star observed, putting a tighter bound on the cosmologically-interesting age of the Universe.

7. Interpreting the Spite Plateau

A further cosmologically-motivated measurement that can be obtained from high-resolution stellar spectra comes from a study of the lithium abundances in stars. Spite & Spite (1982) found that metal-poor main-sequence turn-off stars in the Milky Way all seem to have remarkably similar abundances of lithium. The natural interpretation of this common value is that it reflects the amount of the element produced by primordial nucleosynthesis in the Big Bang, but unfortunately the measured abundance is around a factor of five lower than that predicted by current cosmology (Cybert, Fields & Olive 2008). So, either there is something fundamentally astray in our understanding of the Big Bang, or some process had systematically depleted Galactic levels of lithium before even these metal-poor stars had formed.

One way to discriminate between these possibilities would be to make similar measurements in another galaxy, to see whether they contain the same level of lithium (as would be predicted if it is truly primordial), or different abundances (if something in the more local environment had suppressed the element before the metal-poor stars had formed). Unfortunately, this is a painfully difficult measurement to make, since it requires high resolution spectra of weak lines in intrinsically faint stars. However, with the unprecedented collecting area of the E-ELT, and picking on our nearest neighbour galaxy the Sagittarius Dwarf, it becomes possible. Even then, it will require several nights of integration to obtain the requisite signal-to-noise ratio for the faint spectral features produced by lithium, but with a suitable multiplexing spectrograph to obtain a number of Sagittarius Dwarf turn-off stars simultaneously, it is a viable proposition that could potentially overturn our current picture of cosmology.

8. Resolved Stellar Populations

As mentioned in the Introduction, one of the factors driving the specifications of the E-ELT was to be able to resolve individual stars all the way out to the closest clusters of galaxies. Once individual stars have been detected, every astronomer's immediate instinct is to place them on a colour-magnitude (CM) plot. At galaxy cluster distances with the old stellar populations typically found in cluster galaxies, we will struggle to get to faint enough luminosities to detect many of the features in the CM diagram,

but even just the red giant branch offers a useful diagnostic for the metallicity distribution in these systems. Once we start looking at the relative populations of the asymptotic giant branch and different colours of sub-giant, each of which varies differently with the age of the stellar population, we can start to obtain at least a crude measure of the age distribution in these galaxies as well.

For more nearby systems, where we can obtain photometry all the way down to the main-sequence turn-off, we will be able to construct a complete and reasonably accurate star formation history of a galaxy in a manner that is currently only possible in very nearby systems (Cole et al. 2007). Such analysis of a galaxy's creation is sometimes referred to as "galactic archeology," but the exciting aspect here is that the measurement is so direct that what we will be doing is much more akin to reading a historical record rather than attempting an archaeological reconstruction from fragmentary evidence.

9. A Cautionary Note

This review has briefly outlined a number of the local-Universe science programmes that could be undertaken with the E-ELT. Clearly, invaluable results would be obtained from such studies, but I must admit that I find some of them a little disappointing in their scope. They tend to be rather conservative in what they seek to do, simply pushing the envelope of understanding from existing measurements into new physical environments. If we are going to spend a billion euros on a project like this, we surely have to do even better to justify the expenditure. And, with a telescope that is as large a leap forward as the E-ELT, we really should be able to do just that. So, my plea at the end of this review is that we should be more innovative and ambitious in our ideas for this telescope.

Let me give one example of the kind of crazy idea that I think we should be considering. A long-running question in the study of galaxies has been the details of their mass distributions, and how that mass might be divided between luminous and dark components. For spiral galaxies, the rotation curve provides a straightforward diagnostic, but studies of elliptical systems are more complex, with dynamical measures facing the uncertainty of the orbits followed by the tracer, while other techniques such as a gravitational lensing and measuring the properties of hot X-ray gas are not really suitable for the more ubiquitous low-mass ellipticals. An innovative alternative was put forward by Stiavelli & Setti (1993), who pointed out that the light escaping from radius r in an elliptical galaxy would lose energy as it does so, resulting in a gravitational redshift of

$$v_{\text{grav}}(r) \sim -\Phi(r)/c, \quad (1)$$

thus offering a direct probe of the gravitational potential $\Phi(r)$, and hence the mass distribution of the galaxy. The signal involved is quite small, and is further diluted by line-of-sight projection effects, but none-the-less should produce systematic redshifts in the mean velocities of stars

at small projected radii. Coggins (2003) showed that such redshifts are essentially undetectable in the integrated spectrum of an elliptical galaxy. However, he also calculated that for a compact elliptical like M32 one should obtain a net redshift of $\sim 3 \text{ km s}^{-1}$ per decade in projected radius. While such a signal is quite small compared to the random velocities of individual stars, averaging together a few thousand stars at each radius would quickly beat down the uncertainty to a point where this shift in the mean velocity is easily measured. In fact, by observing individual stars and drawing on the spectral finger-printing techniques of Sect. 5, we can do even better by targeting those whose chemical abundances indicate they are at intrinsically small radii (e.g. Baes et al. 2007), thus significantly reducing the diluting effects of line-of-sight projection and further increasing the redshift signal. The E-ELT's combination of high spatial resolution to pick out individual stars, large collecting area to obtain adequate numbers of photons from each star, and multiplexing instruments to record high resolution spectra from large numbers of stars, could allow this kind of crazy idea to become a reality.

We have a good few years before the E-ELT becomes a reality, so let's spend at least a few of them thinking such out-of-the-box thoughts rather than just rehashing a safe agreeable science programme.

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